

Advanced Power Plant Using High Efficiency Boiler/Turbine



BEST PRACTICE BROCHURE

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BEST PRACTICE BROCHURE:

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*Changshu Power Station, China
3 x 600MWe Mitsui Babcock once-through supercritical wall-fired
boilers*

OVERVIEW

This Best Practice Brochure describes the best commercially available, pulverised fuel combustion advanced supercritical (ASC) boiler/steam turbine power plant technologies suitable for clean coal power generation, in home and export markets, for both new build and retrofits. It describes the performance of such plants, including efficiency, carbon dioxide emissions, air pollution controls/emission levels, and their flexibility and

availability. It demonstrates how these technologies are based on many reference plants worldwide for a wide range of coal types (from semi-lignite to semi-anthracite) and explains how these best practice technologies can be adapted for biomass co-firing and carbon dioxide capture and storage.

The best available technology (BAT) with steam conditions of 300 bar / 600°C / 620°C gives an efficiency of 46-48% net (LHV basis). This limit is primarily determined by the combination of best practice boiler and turbine technologies, with the best commercially available materials for the higher temperature parts of the boiler, turbine and pipework. Site specific requirements such as location, ie inland or coastal, also being a factor in determining how high an efficiency can be achieved.

Such a BAT PF-fired power plant would be fitted with high-quality selective catalytic reduction (SCR) for NO_x reduction, flue gas desulphurisation (FGD) for SO₂ reduction and an electrostatic precipitator (ESP) or baghouse filter, as appropriate, for particulates removal. The BAT PF-fired ASC power plant would meet or better the EU Large Combustion Plant Directive (LCPD) on emission level values applicable from 2008.

For these BAT temperatures ferritic, martensitic and austenitic steels are utilised, building on the growing experience base of these materials over the last 15 years.

Future plant currently under development in the Advanced ('700°C') PF Power Plant Project

(AD700) will achieve 50-55% net efficiency. To achieve these efficiencies a step-change in steam conditions to 350 bar / 700°C / 720°C is necessary and this requires the use of nickel alloys in the highest temperature regions of the superheater, reheater, turbine and pipework. AD700 ASC PF boiler and turbine technology is expected to become available before 2010.

This Brochure describes the evolution of the technology and gives examples of the current state-of-the-art and the key features of the best practice. More detail is given on important design aspects of the boiler and turbine, including the choice of materials used for BAT steam conditions. The benefits of this clean coal technology are summarised and it is shown how the technology is continuing to develop. These evolutionary developments include materials for 600°C-650°C, Mitsui Babcock's innovative Posiflow™ vertical tube furnace design, the AD700 ASC PF power plant and carbon dioxide capture technologies - amine scrubbing and oxyfuel firing.

1. INTRODUCTION

Over the period 2003-2030 it is estimated that nearly 1400GWe of new coal-fired capacity will be built worldwide, with two-thirds of the new capacity in developing countries. Coal-fired power plants are expected to provide about 38% of global electricity needs in 2030; close to today's share of global electricity supply needs.¹

This growth in coal-fired power generation will lead to a large increase in emissions of carbon dioxide and runs counter to the environmental need to reduce greenhouse gas emissions. Attention is therefore being given to how carbon dioxide emissions from coal-fired plant, existing and new, can be abated. It is widely agreed that two complementary approaches are possible. These are efficiency improvements (to generate more power for less carbon dioxide) and carbon dioxide capture and geological storage (CCS), see Figure 1.

The first track (efficiency improvement) can be implemented relatively quickly by adoption of the best available technology (BAT) (new build or retrofit) whilst the second track (carbon dioxide capture and storage) is a longer-term measure, dependent on the successful demonstration of capture and storage technologies.

Typically, older pulverised fuel (PF) power plant, designed with subcritical steam conditions, deliver overall net power plant efficiencies of 30-35% (LHV)¹. The current BAT PF-fired advanced supercritical (ASC) plant with steam conditions of 300 bar / 600°C / 620°C gives an overall net plant efficiency of 46-48%, dependent upon site specific issues such as location. This limit is determined by the combination of best practice boiler and turbine technologies with the best commercially available materials for the higher temperature parts of the boiler, turbine and pipework. Future PF-fired ASC power plant currently under development in the AD700 project (see Section 7) will achieve 50-55% net (LHV) efficiency. To achieve these efficiencies a step-change in steam conditions to 350 bar / 700°C / 720°C is necessary and this requires the use of nickel alloys in the boiler, turbine and pipework. The trend for increasing efficiency is shown in Figure 2.

As efficiency increases, specific carbon dioxide emissions decrease from almost 1100g/kWh at 30% net (LHV) efficiency to about 700g/kWh at 46% net (Figure 3), a reduction in CO₂ emissions of just over 36%. Coal consumption is similarly reduced.

2. STATE-OF-THE-ART

The best practice state-of-the-art is determined by the commercial availability of boilers, turbines and pipework which can be guaranteed to meet customers' requirements for efficiency, emissions and performance.

Plants are custom-designed taking account of the location, climate, cooling water

¹ World Energy Outlook 2004, IEA, ISBN 92-64-10817-3 (2004)

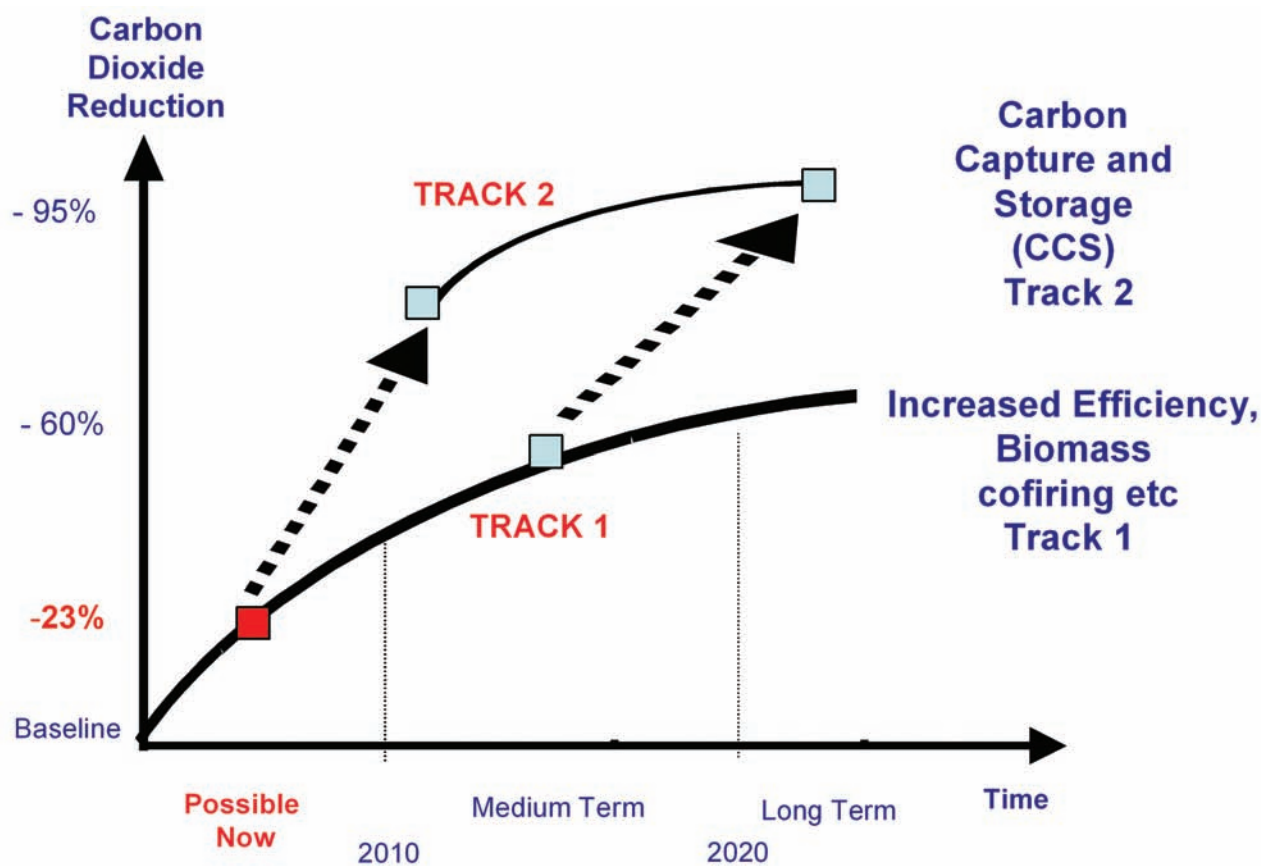


Figure 1. CO₂ abatement from fossil fuels - twin-track approach

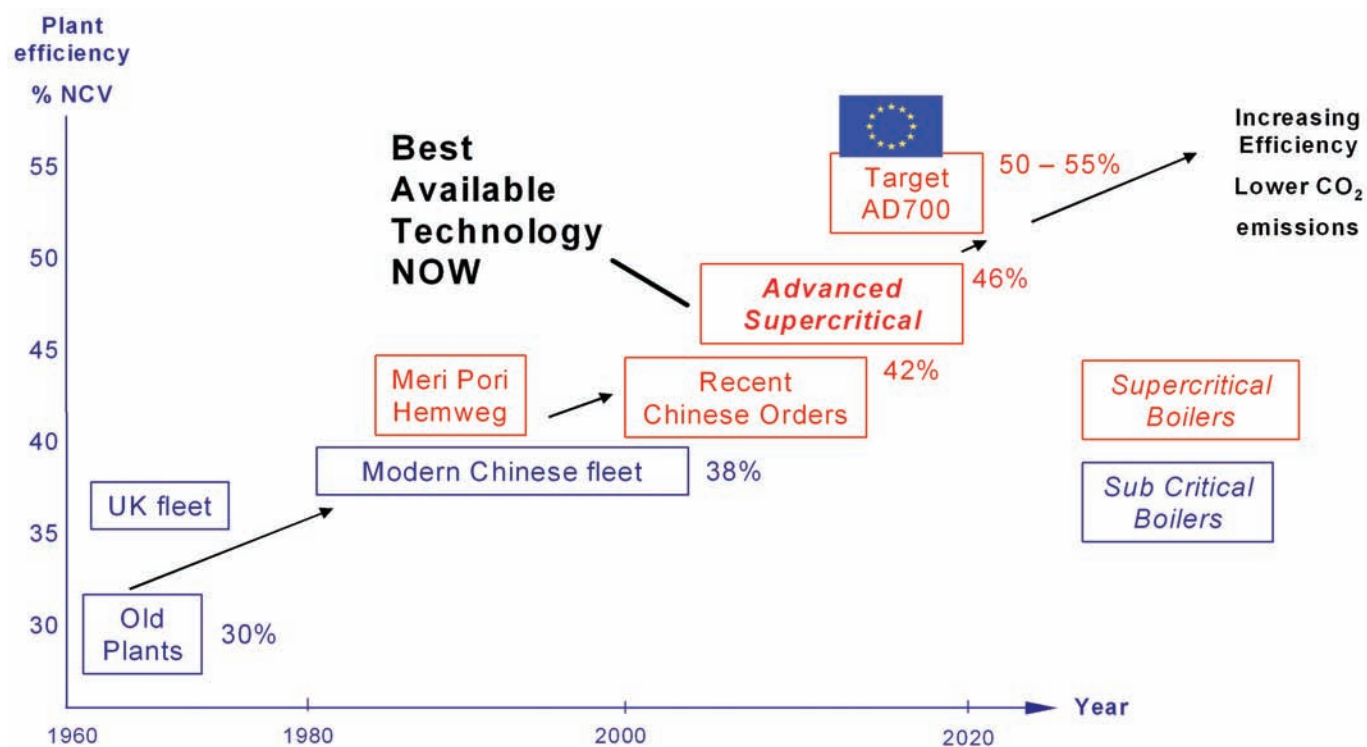


Figure 2. Progressive improvement of net efficiency of boiler turbine coal-fired (PF-fired) power plant

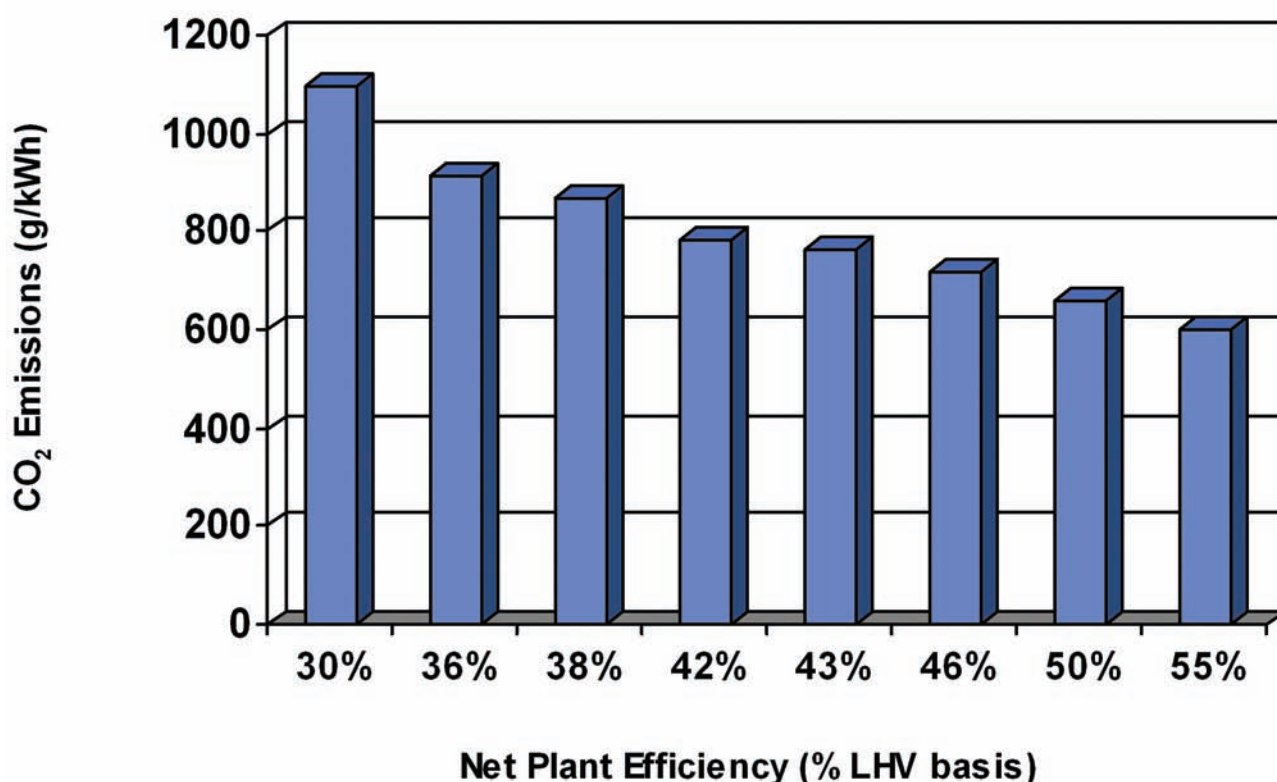


Figure 3. Decrease in CO₂ emissions with increasing net plant efficiency

temperatures and range of coals/fuel to be burned, all of which influence the overall plant efficiency. Examples of best practice supercritical boiler/turbine technology are found in Europe, Japan and, more recently, in China.² A summary of some of these examples are given in the table on page 5.

The main fuel for these plants is pulverised coal (ie pulverised fuel, PF-fired) except for Avedøreværket and Skærbæk which are mainly fired on gas.

DTI Best Practice Brochure BPB003 provides further information on the supercritical boiler technology at Hemweg Power Station.³

In Europe, the state-of-the-art has progressed as boiler and turbine materials have been developed to cope with the increasing pressures and temperatures of more advanced plant. The introduction of the modern 9-12

chromium martensitic steels for headers, main-steam and reheat pipework, first in the UK for plant retrofits, then in Denmark for the plants described above, has allowed steam conditions to be increased.

A consensus has emerged among boilermakers and turbine-makers, including Mitsui Babcock and Alstom Power, that the BAT for supercritical boiler/turbine power plant using the best commercially available materials would have steam conditions at the boiler superheater/reheater outlets of approximately 300 bar / 600°C / 620°C and, for example, at an inland Northern European location, would have an overall plant efficiency of about 46% net (LHV). Such a plant would be fitted with selective catalytic reduction (SCR) for NO_x reduction, flue gas desulphurisation (FGD) for SO₂ reduction and an electrostatic precipitator (ESP) for reduction of particulates, and would meet or better the EU Large Combustion Plant

² Fossil Fuel Power Generation – The State of the Art, published by the EU PowerClean R, D and D Thematic Network, 30 July 2004, Section 3

³ DTI Best Practice Brochure No. BPB003, "Supercritical Boiler Technology at Hemweg Power Station" DTI/Pub URN 01/699, March 2001

Country	Power Plant	Unit Rating MWe net (gross)	Steam Press (bar)	Main Steam Temp (°C)	Reheat RH1 Steam Temp (°C)	Reheat RH2 Steam Temp (°C)	Efficiency (% net LHV)
Denmark	Avedøreværket 2	390	300	580	600	—	48.3
Denmark	Nordjylland 3	411	285	580	580	580	47
Denmark	Skærbæk 3	411	290	582	580	580	49
Holland	Hemweg 8	630	260	540	568	—	42
Finland	Meri Pori	550	244	540	560	—	45
Germany	Staudinger	509	262	545	562	—	43
Germany	Niederaussem K	965	275	580	600	—	45.2
Japan	Tachibanawan	1050	250	600	610	—	43.5
Japan	Isogo	600	266	600	610	—	Not Available ?
China	Changshu	600	259	569	569	—	42
China	Wangqu	600	247	571	569	—	43
USA	Tanners Creek	580	241	538	552	566	39.8
USA	Duke Power	(1120)	241	538	538	—	Not Available ?

Directive on emission level values applicable from 2008.

In addition to developing new advanced supercritical power plants, Mitsui Babcock and Alstom Power have jointly developed the concept of retrofitting best available supercritical boiler/turbine technology to existing coal PF-fired power stations and, furthermore, of designing such plants to be suitable for fitting of carbon dioxide capture equipment.

The state-of-the-art supercritical boiler/turbine steam plant described above includes the following key features:

Overall/balance of plant:

- High plant cycle efficiency of ~ 46% net (LHV); inland plant; based on steam parameters of approximately 300 bar / 600°C / 620°C
- Main steam and reheat pipework in materials to accommodate the BAT steam conditions
- Plant layout designed to accommodate carbon dioxide capture plant.

Boiler:

- Designed to accommodate the properties of a range of coals including sub-bituminous,

bituminous or semi-anthracite and to provide the option of biomass co-firing

- Combustion system to optimise burn-out and minimise NO_x
- Materials for furnace walls, superheater and reheater with strength and corrosion resistance to accommodate the BAT steam conditions and resulting flue gases
- Spiral wound furnace utilising smooth bore tubes (or innovative vertical tube furnace, Posiflow™, described further in Section 7).

Turbine:

- Valve chest, turbine casing and rotor materials to accommodate the BAT steam conditions
- Blading of advanced geometry to maximise efficiency.

More detail on each of the above is given in the following sections.

3. THE OVERALL POWER GENERATION CYCLE AND PERFORMANCE

The majority of existing coal-fired power generation plant around the world is based on

the conventional single reheat thermal cycle with subcritical main steam pressure in the range 160-180 bar and main/reheat steam temperatures both in the range 535-565°C.

The thermodynamic efficiency of the conventional (subcritical) single reheat cycle can be improved significantly if the average temperature at which heat is added to the cycle is increased. The most obvious method of increasing the average temperature at which heat is added to the cycle is by increasing main and reheat steam temperatures. Every 20K rise in both main and reheat steam temperatures will improve relative cycle efficiency by approximately one percentage point over a wide range of temperatures and pressures, as shown by Figure 4 below.

In a reheat cycle, increasing the main steam pressure will always improve the cycle efficiency and this is the incentive for using supercritical steam conditions (>222 bar). However, it will be recognised from Figure 4 that the thermodynamic benefit of increased main steam pressure at a given temperature is subject to diminishing returns because the significant reduction in volumetric flow at these conditions leads to shorter and wider turbine blading that is subject, on a relative basis, to higher passage boundary losses and increased

steam path leakage. These blading losses act to offset the thermodynamic benefits of elevated steam conditions with increased main steam pressure. It is therefore generally accepted that increasing the main steam pressure at superheater outlet above 300 bar with the BAT main/reheat temperatures of 600°C / 620°C does not offer any further practical economic benefits. Similarly, there is an optimum main steam pressure for the AD700 advanced supercritical plant under development using main/reheat temperatures of 600°C / 620°C of 350 bar for a single reheat plant. Exceeding this value is unlikely to provide worthwhile efficiency improvements. In each of these cases, the corresponding turbine cycle must be arranged to provide boiler feedwater at the correct pressure and temperature for optimum boiler efficiency, and will normally incorporate a feedwater heater above the reheat point using steam extracted from the high pressure (HP) turbine.

Figure 4 shows that the overall improvement in relative cycle efficiency obtained purely from increasing steam conditions at turbine inlet from 160 bar / 540°C / 540°C to 290 bar / 600°C / 620°C will be in excess of 7%. This corresponds to a reduction in both fuel burned and boiler emissions of about 18% for a 46% net efficiency ASC plant compared to a 38%

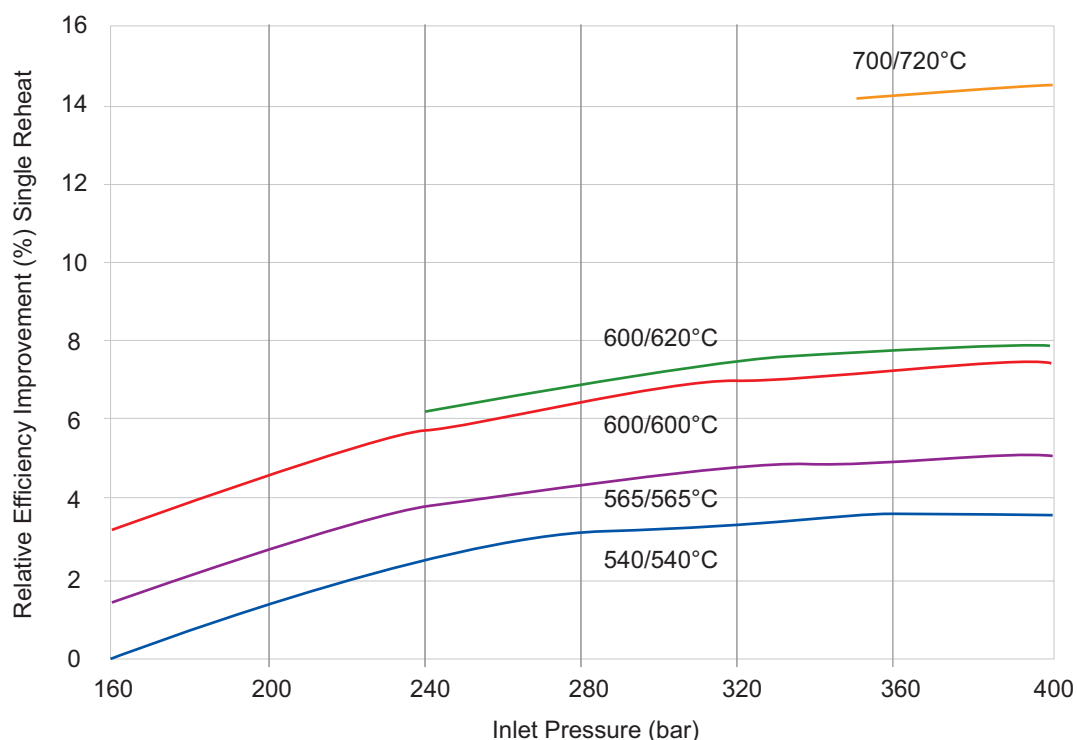


Figure 4. Effect of steam conditions on cycle efficiency (for single reheat units)

net efficiency subcritical plant. From Figure 4 above, the AD700 ASC cycle (not yet commercially available) would offer a further step benefit in relative efficiency improvement of about seven percentage points, giving a further reduction in fuel burned and boiler emissions of about 15% compared with a 46% net efficiency ASC plant.

New power plants designed for operation at these elevated steam conditions can also take advantage of advanced turbine blading technology and state-of-the-art condenser configurations, providing very low turbine exhaust pressures (ie high vacuum conditions in the heat sink) to provide maximum power generation from the energy input, with the potential to provide large quantities of low pressure process steam extracted from the turbine for district heating, industrial use or on-site CO₂ capture plant.

Existing conventional coal-fired power plant can be modified to operate at these ASC steam conditions by replacing the existing boiler (re-using the existing support structure, coal handling plant, coal mills, etc) and retrofitting the high temperature main and reheat steam valves and the HP and intermediate pressure (IP) turbine sections, using advanced materials and state-of-the-art blading. Retrofitted generating plant, including re-optimisation of the feedwater heating system with a heater above the reheat point, will give plant efficiency levels approaching those of new ASC plant based on similar cycle configurations and subject to the status of any retained equipment.

4. ADVANCED SUPERCRITICAL BOILERS

BOILER DESIGN

The state-of-the-art ASC PF-fired boiler design is based on the established Mitsui Babcock two-pass layout once-through supercritical unit utilising the Benson principle (see Figure 5).

The two-pass opposed wall-fired furnace/boiler layout has been widely used in subcritical and supercritical boilers built by Mitsui Babcock and

its licencees in Denmark, Holland, Finland, South Africa, India, Japan and China. More than 111,900MWe net of such plant is operational and as at October 2005 Mitsui Babcock has more than 24,000MWe (net) either in the process of design or construction. The two-pass technology is used by former Mitsui Babcock licensees in Japan and it is widely favoured in the USA.

A two-pass boiler arrangement offers a number of benefits, including the following:

- No high-temperature tube bank supports are necessary; therefore the two-pass design can offer a higher FEGT and hence an increased utilisation of heat transfer surfaces compared with that for a tower boiler.
- The vertical pendent superheater tube design incorporates finned tips which allows avoidance of ash-slag adhesion.
- The rear pass dimensions of the two-pass boiler can be optimised for gas side velocity to meet the exact heat transfer requirements without erosion. This cannot be done on a tower boiler as the dimensions of the convective pass are constrained by the furnace dimensions.
- Pipework is shorter due to the reduced boiler height compared to an equivalent PF-fired tower boiler.

The boiler is sited in a boiler house with the pressure parts suspended within the boiler structure. The boiler house accommodates the coal bunkers, coal feeders, coal milling plant and the forced draught and primary air fans and air heaters.

The furnace dimensions are chosen to meet the requirements of low NO_x emissions in the flue gases whilst maximising burnout to minimise the amounts of unburned carbon-in-fly-ash for the given fuel fired.

In the combustion zone of the boiler, the membrane wall is spiral wound, utilising smooth-bore tubing. This inclined-tube arrangement reduces the number of parallel paths compared with a vertical-wall arrangement and therefore increases the mass flow of steam/water mixture through each

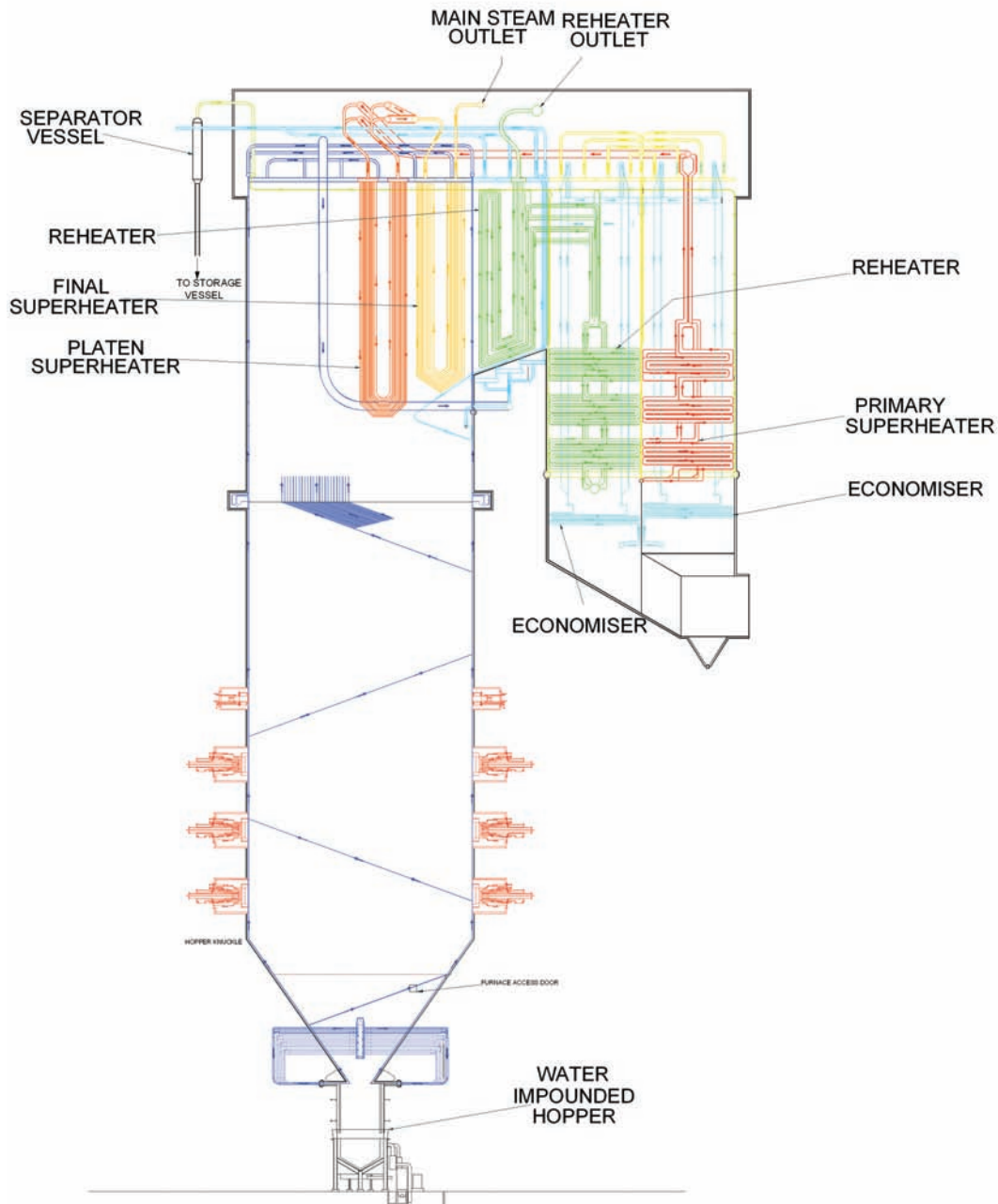


Figure 5. Mitsui Babcock two-pass advanced supercritical (ASC) boiler

smooth-bore tube. The high mass flow improves heat transfer between the tube metal and the fluid inside to maintain adequate cooling of the tube metal, despite the powerful radiant heat flux from the furnace fireball. In the upper furnace area, the heat flux is much lower and the transition is made from spiral wound to vertical tubing, via a transition header.

The supercritical boiler itself is designed for a high degree of operational flexibility in its load regime. This allows the plant to operate in a daily load-following mode and, as is often required, can handle a wide range of coal

types. This flexibility of design is achieved by careful selection of pressure part materials and by design features, including stub headers, in order to avoid the use of thick-section components in critical areas. In this way, the cyclic stresses that cause fatigue are minimised, as a combination of these, with high-temperature creep, could shorten the life of these components.

The boiler is operated in a modified sliding-pressure mode where the turbine inlet pressure is controlled to a level that varies with the unit load. Lower pressures at part load enable

savings in feed pump power to be realised and throttling losses in the turbine control valves to be minimised. For start-up purposes and low load operation, the boiler has a circulation system incorporating circulating pumps.

The boiler is equipped with three superheaters with interstage spray-type attemperators and two reheater banks. The economiser is a horizontal, multi-loop bank with extended surface tubes.

Although the superheater and reheater stages are similar to those of a two-pass subcritical boiler design, the increases in pressure and temperature require either thicker sections or higher-grade components. The latter solution is chosen in order to minimise fatigue damage and reduce weight.

A summary of typical generic and specific materials for ASC boilers is given below.

BOILER MATERIALS

The best commercially available steels allow the construction of boiler plant for steam conditions of 300 bar / 600°C / 620°C, for a wide range of coals, even those producing an aggressively corrosive flue gas.

The various components of the boiler are employed over a range of temperatures, pressures and corrosive atmospheres, and oxidation conditions, and the range of alloys necessary to best meet the design demands covers the simple carbon manganese (CMn) steels, low alloy steels, advanced low alloy steels, the 9-12Cr martensitic family and the austenitic range with chromium varying from 18% to in excess of 25%.

Simple carbon manganese steels are utilised at lower temperatures such as the reheater inlet but as component temperatures increase, it is necessary to move to low alloy steels such as SA213 T22 which, like the CMn steels, have been employed in boiler construction for decades.

Moving to components at even higher temperatures and considering other manufacturing restrictions leads to the introduction of more modern steels that have been referred to as creep-strength enhanced ferritic (CSEF) steels⁴, which exhibit very high creep strength by virtue of a fine dispersion of creep strengthening precipitates.

Two specific alloys within this family are T23 per ASME code case 2199 and T24 per ASTM A213. Both are based on the much used T22 or 2.25% chrome steel, but in the case of T23 modified by the addition of 1.6% tungsten and the reduction of molybdenum and carbon contents with the addition of small amounts of niobium, vanadium and boron. T24 also has reduced carbon but with additions of vanadium, titanium and boron.

These variations to the T22 specification produce steels with very high creep strength, comparable to T91 but with another particular advantage confirmed by the low carbon content: no post weld heat treatment (PWHT) of these steels is required.

This very attractive property makes these steels particularly suitable for high-temperature application in membraned areas where the need for PWHT, if it were necessary, would create significant manufacturing difficulties.

Likely candidates for components from these alloys would include the furnace water walls and furnace roof. Other, non-membraned items such as the inlet end of the superheater can also utilise these alloys simply due to their excellent creep strength.

Both alloys have an extensive laboratory-based background, but Mitsui Babcock has employed the T23 alloy at temperatures pertinent to 300 bar / 600°C / 620°C, albeit at subcritical conditions, and therefore has a preference for this variant.

⁴ J F Henry, J M Tanzosh, M Gold, "Issue of Concern to ASME Boiler & Pressure Vessel Committee TG on Creep Strength Enhanced Ferritic Steels and Remedies Under Consolidation"

Another CSEF steel which has been used in Mitsui Babcock boilers for nearly 20 years since it was first 'demonstrated' in a retrofit application at Drakelow⁵ is steel 91, which is employed in tubes as well as headers and pipework. This so-called modified 9Cr has an excellent creep strength, but the maximum temperature of application is limited by steam-side oxidation. In particular, the temperature in heat transfer tubes is limited by the fact that the internal oxide in the tube acts as a thermal barrier which increases the metal temperature, thus increasing the oxidation rate.

The same oxidation controlled temperature limit applies to a further modified 9% chromium steel, T92, which has an addition of 2% tungsten, a reduction in molybdenum so as to adjust the balance of ferritic-austenitic elements, and the addition of micro-alloying amounts of boron.

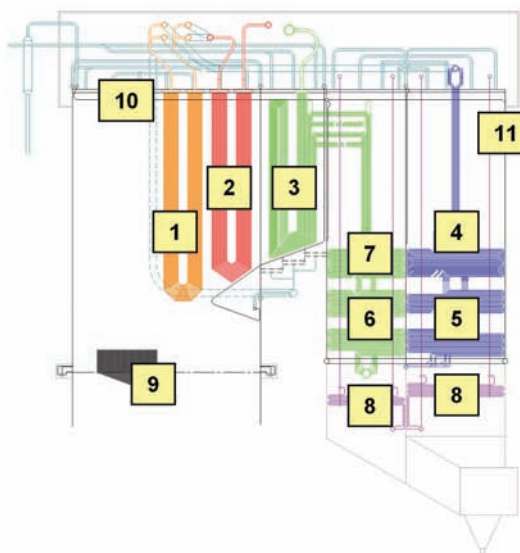
T92 is the creep strongest of all the so-called CSEF 9-12% Cr steels.

In the case of the very high temperature components such as the superheater and reheater, the choice of material is more likely to be dictated by the flue gas corrosiveness rather than simple stress rupture characteristics. Furthermore, such components are most likely to employ a range of materials possibly employing lower alloys at the inlet which is at a lower temperature and graduating to higher alloy at the outlet high temperature end. It is common to have lead tubes in the highest grade of all.

Tp347 is a frequently used 18% Cr 11% Ni austenitic alloy for which there is considerable experience in Mitsui Babcock boilers, but for aggressive atmospheres higher chrome grades such as Tp310HNBn (HR3C) with 25% chromium and 20% nickel would be required.

The Mitsui Babcock preferred alloys for heating surfaces are presented in the table in Figure 6 below.

Advanced Supercritical Tube Materials (300 bar/600°C/620°C)



* SA213 T92 used for outlet tube stub connections

Ref	Heating surface	Material	Design temp (°C)
1	Platen SH	SA 213 TP347H/ TP310HCbN/ T92*	640
2	Final SH	SA 213 TP347H/ TP310HCbN / T92*	650
3	Final RH	T22/ T91/ TP347H/ TP310HCbN/ T92*	680
4	Prim SH	SA 213 T91	550
5	Prim SH inlet	SA 213 T23	530
6	RH inlet	SA 210C	470
7	RH	SA 213 T12	540
8	Econ	SA 210C	375
9	Water wall	SA 213 T12/ T23	515
10	Furnace roof	SA 213 T23	510
11	Rear cage	SA 213 T23	510

Figure 6. Advanced supercritical (ASC) boiler tube materials

⁵ W M Ham, B S Greenwell, "The Application of P91 Steel to Boiler Components in the UK", ECSC Information Day, November 1992

In the case of headers and pipework, in general, the same range of commercially available steels are produced as pipes and forgings and are thus available to the designer. However, different consideration must be given to these 'thick' components which generally do not have a heat transfer function.

Due to the atomic lattice structure there is an inherent difference in the coefficient of expansion, and the thermal conductivity of austenitic materials, in comparison with ferritic. The higher expansion and lower conductivity of austenitics are such as to induce twice the stress in the event of a temperature transient than would be the case in a ferritic component of the same dimension.

For this reason ferritic materials such as P91 and P92 are preferred, and these materials can be employed in non-heat transfer conditions up to 620°C, ie as headers as opposed to tubes.

EMISSIONS: NO_x, SO_x and particulates

Emissions of air pollutants can be controlled to levels much below those of current plant, within the EU LCPD limits applicable from

2008 and down to levels comparable to or better than competing technologies such as Integrated Gasification Combined Cycle (IGCC).

Emission levels for best practice supercritical plant are shown in Table 1. These limits are achieved using well-proven emissions control technologies:

NO_x emissions: Emissions are reduced using a combination of low NO_x burners, boosted overfire air and back-end clean-up by selective catalytic reduction in a DeNO_x plant using ammonia. For retrofit applications where the footprint of SCR equipment cannot be accommodated, Mitsui Babcock offers an in-furnace autocatalytic process known as NOxStar™.

SO_x emissions: SO₂ is captured using wet limestone-gypsum flue gas desulphurisation (FGD). The end-product, gypsum, is often saleable for use in wallboard.

Particulate emissions: More than 99.9% of particulate dust is removed via an electrostatic precipitator (ESP).

Table 1. Emission levels for best practice supercritical boiler/turbine plant

Emission (@6% oxygen dry vol basis) Units are mg/Nm ³	EU LCPD limit – existing plant (from 2008)	EU LCPD limit – new plant (from 2008)	Levels currently offered [†]
NO _x	500	200	38
SO ₂	400	200	100
Particulates	50	30	20
PM ₁₀	-		20
Mercury	-		4.5 x 10 ⁻⁶ kg/MWh
VOC	-		38
CO	-		11
H ₂ SO ₄	-		3.75

[†] = Typical values being offered for new plant: exact figures depend on coal composition.

5. ADVANCED SUPERCRITICAL TURBINES

BACKGROUND

The basic construction of single reheat large steam turbines for coal-fired power plant was established over 30 years ago. This construction, designed originally for operating at conventional steam conditions, has achieved very high standards of reliability and operability through continuing development and feedback of operating experience. The same basic design therefore provides a very sound reference base for high output applications at ASC operating conditions taking advantage of advanced materials and design refinements (see Figure 7).

ADVANCES IN MATERIALS

Steam turbines for ASC steam conditions require application of advanced alloy steels for the HP and IP turbines and for the main and reheat steam admission valves.

The maximum metal temperatures in high temperature steam turbine components are limited by the applied stress and the requirement for a component lifetime of at least 200,000 hours. The principal material property determining the maximum temperature is the long-term creep rupture strength.

The most critical components at elevated temperatures are the valve chests and turbine casings (operating under high internal steam pressures) and the turbine rotors and blading (operating under high centrifugal load). With respect to pressure containment, the HP turbine casings tend to be the most limiting, whilst for the rotating components, the IP rotor, being of larger diameter and with longer blades, requires the more careful design in the high temperature regions. In contrast, the low pressure (LP) turbines can use the same technology as conventional steam turbines, because the steam conditions at inlet to the LP sections can be maintained at similar levels to subcritical steam generating plant.

Today's state-of-the-art steam turbines are based on the exploitation of advanced 9-12% Cr martensitic steels for rotors and casings, with nickel-based alloys or high-strength austenitic steels being required only for the early stages of blading. In both Europe and Japan, a first generation of advanced martensitic steels was developed in the mid-1980s and saw first commercial applications in plant entering service in the mid-1990s. These steels were based on optimised additions of Cr (9-10%), Mo (1-1.5%), W (~1%), V (~0.2%), Nb (~0.05%) and N (~0.05%), and they enabled steam temperatures to be increased

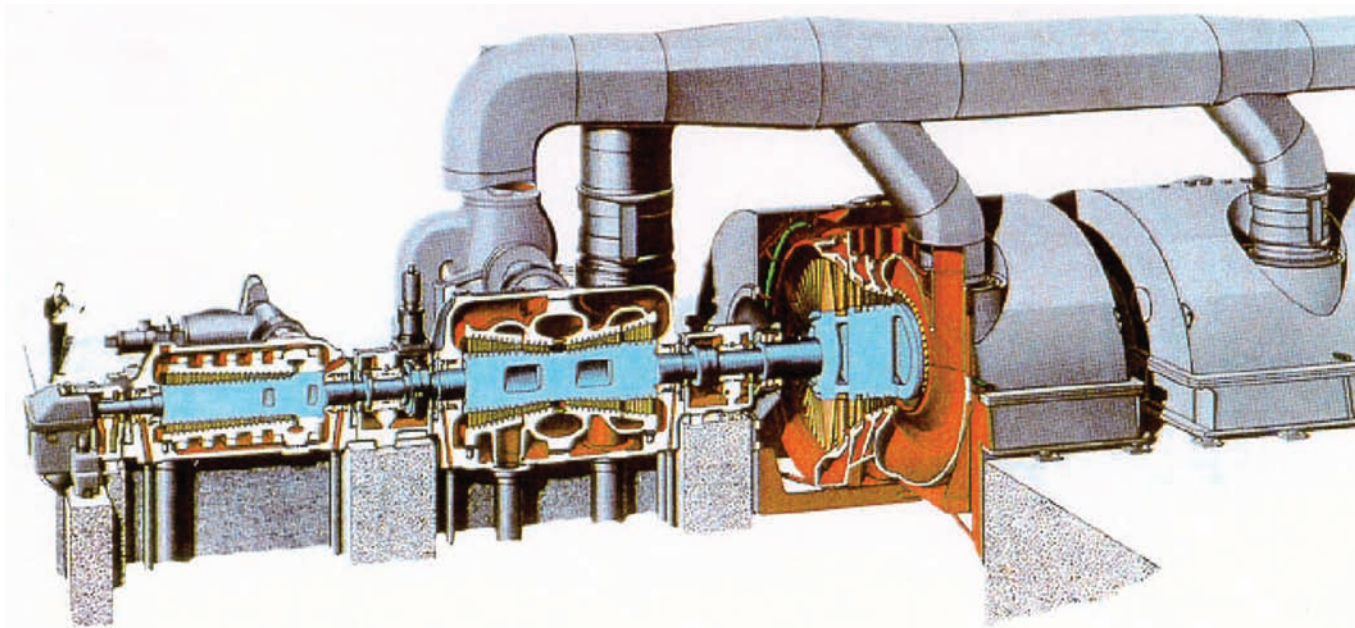


Figure 7. 900MW steam turbine for ASC steam conditions

to around 600°C. A second generation of alloys has been developed based on additions of boron (~100ppm), in some cases with higher levels of W, and with additions of cobalt to ensure a fully martensitic microstructure. The greater creep strength of this second generation of alloys has enabled temperatures of 620°C to be achieved. These new steels have not yet been applied in operating plant but full-scale prototype components have been manufactured and tested as part of development programmes.

As temperatures increase, the rate of oxidation of turbine materials rises. However, the 9-12% Cr steels are significantly more resistant to oxidation in steam than the low alloys steels successfully used in the UK at temperatures up to 565°C, for the last 40 years. Nevertheless, at the very highest temperatures, increases in the rate of oxidation can be expected. In turbine components this is of limited practical significance except where very close clearances are required, for example, in some valve components. In these cases coating solutions are already commercially available.

DESIGN FEATURES

Modern HP and IP turbines for both conventional and supercritical applications at moderate temperatures use single-piece rotor forgings. The application of welded rotor technology in these sections (with rotors made by welding together several forged sections to form a compact shaft with low body stresses) provides the capability to introduce 10% Cr steel sections for the hottest areas adjacent to the steam inlet zones of the HP and IP turbines, with conventional 1% CrMoV material for the outboard sections (see Figure 8).

Distortion of turbine casings during thermal transients (eg in start-up or rapid load changes) can damage radials seals between the rotor and stationary parts, especially if the fixed blades are mounted directly into the casings. The cylindrical symmetry obtained from a 'shrink-ring' closure system of the HP inner casing (Figure 9) avoids the need for bolted joint flanges and ensures that thermal

distortion of casings is minimised with a consequent improvement in operational flexibility.

Where applicable, temperature conditioning steam flows are introduced from within the HP and IP turbine cylinders to ensure that steady state metal temperatures in the hottest regions remain within acceptable limits, and to reduce the thermal impact of rapid load changes whilst retaining maximum performance advantage from the advanced steam conditions.

Research and development in the field of steam turbine blading has accelerated rapidly in recent years through the use of computational fluid dynamics tools, supported by confirmatory laboratory testing. Remarkable improvements in turbine internal efficiencies have been achieved and demonstrated in both new and retrofit turbine applications. Retrofitting older generating plant with advanced blading technology offers the potential for substantial performance improvements together with improved reliability, maintainability and plant availability, and there are now many examples of such projects in all competitive electricity generation markets around the world. Typical improvements in relative cycle efficiency from retrofitting 30 year-old steam turbine shaftlines (ie including LP turbines) with advanced steam path components at the original design conditions are in the range of 5-6%, depending on the original design. This improvement would be in addition to the 7% relative cycle efficiency benefit of converting an existing conventional plant for ASC operation (ie about 12-13% total).

New steam turbines (or retrofitted turbines) for ASC applications, in common with conventional steam turbines, must be able to support rapid load changes and have the capability to operate efficiently at part loads. Turbine internal efficiency improvements, discussed above for full load operation, also translate to similar improvements at part loads. Part load efficiency is largely a function of valve throttling loss. New HP turbine modules would therefore ideally be equipped

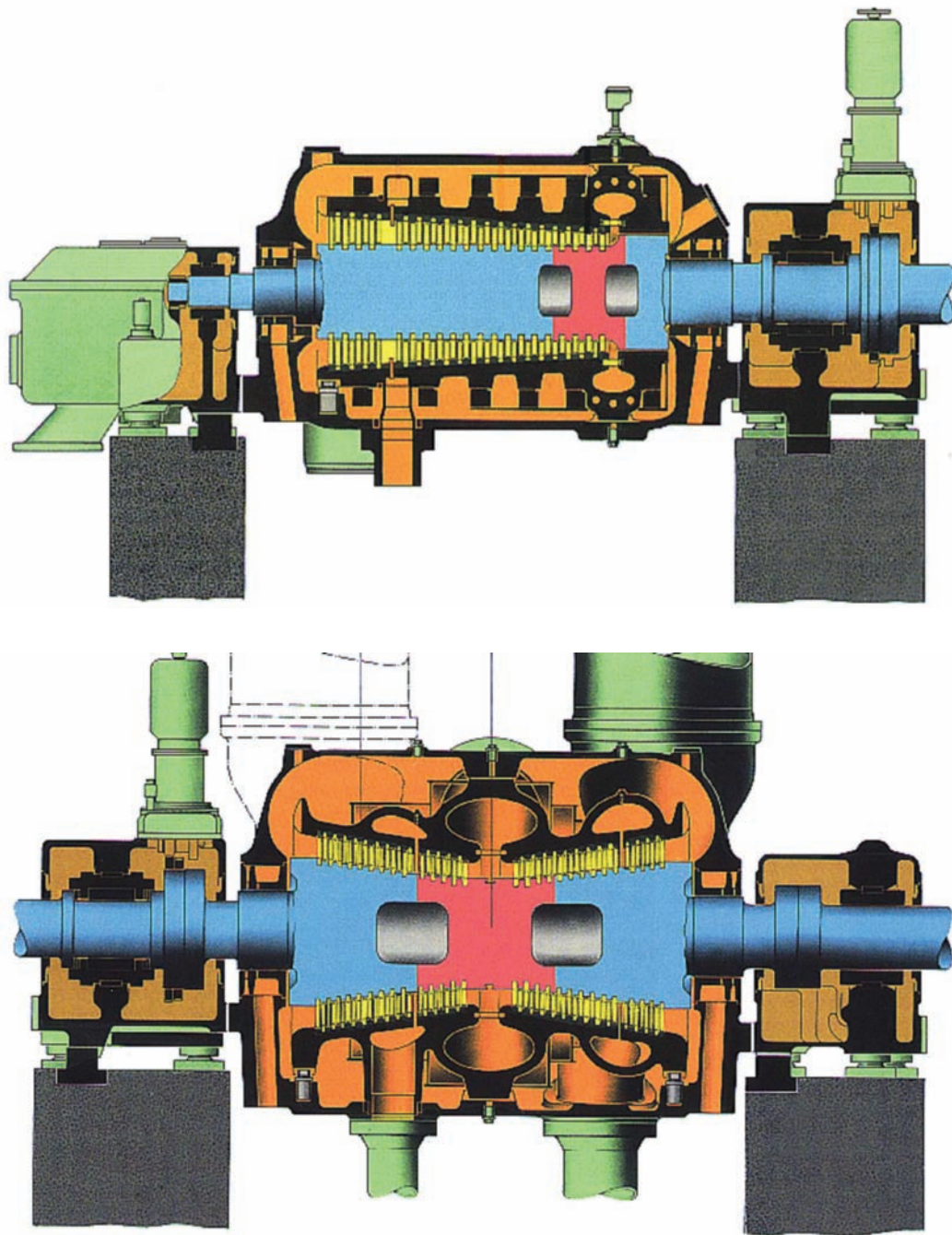


Figure 8. HP and IP turbines with welded rotors using 10% Cr steel in hottest regions

with nozzle control capability to permit the unit to operate with up to 50% of the nozzle arcs closed at part load. This avoids the losses associated with throttling all the turbine governor valves simultaneously. The turbine governor on a new plant would be configured to permit operation in this mode and existing electronic governors can be modified or mechanical governors can be replaced to facilitate conversion of existing plants.

The retrofitted ASC steam turbine equipment would be capable of operating for up to 100,000 operating hours (12 years) between major maintenance inspection outages involving turbine cylinder disassembly. Taking account of minor inspection requirements (eg on the turbine valves) and potentially more frequent overhaul inspections of other re-used equipment, the retrofitted ASC turbine island would be expected to provide an availability of at least 95%.

6. BENEFITS OF ADVANCED SUPERCRITICAL TECHNOLOGY

In this section the benefits of ASC boiler/turbine technology, as summarised in Table 2 below, are explained together with comparisons to older, less efficient plant and alternative clean coal technologies.

REDUCED FUEL COSTS

Fuel costs represent around two-thirds of the total operating costs of a coal-fired power plant. The main impact of the supercritical cycle is to increase the overall plant efficiency, thereby reducing the fuel consumption per unit of electricity generated. For a 600MWe unit with an overall availability of approximately 85%, almost 300,000t/year (~ 18%) of coal are saved by generating in an advanced supercritical boiler with a net cycle efficiency of 46%, compared with that in a typical subcritical boiler with a net cycle efficiency of 38%. This represents a considerable saving with respect to fuel costs for the plant of almost US\$16 million/year (~ £9 million/year assuming a coal price of £30/t).

SIGNIFICANT REDUCTION IN CO₂ EMISSIONS

Growing environmental concerns are complemented by another of the ASC boiler/turbine plant's main selling points: less coal for the same power output means

less CO₂. By utilising state-of-the-art ASC PF-fired power plant, CO₂ emissions will be reduced by about 23% per unit of electricity generated, when compared to existing subcritical plant.

BIOMASS CO-FIRING

Biomass (a CO₂-neutral fuel) can be co-fired with coal in large boiler plant giving coal-based CO₂ reductions of up to 20%.

At relatively low percentages (typically 5-7% in terms of heat input) the biomass can be blended with the coal and then milled and fired through the existing combustion plant.

The capital cost of biomass co-firing equipment is relatively low, and generation risks with enhanced co-firing (ie with around 20% biomass) are reduced when installed in a purpose-designed furnace.

EXCELLENT AVAILABILITY

Typical average availability for modern supercritical plant is close to 85%. However, with the correct commercial drivers in place, greater than 90% is achievable. For example, the availability of the Hemweg 8 plant (630MWe at 260 bar / 540°C / 568°C) was 92% from 1998 to 2000.³ Furthermore, the Posiflow™ once-through boiler demonstrated at Yaomeng⁶ achieved a 100% availability for 17 out of 18 months.

Table 2.

Advanced Supercritical (ASC) Boiler/Turbine Technology Key Features / Benefits Include :

- Reduced fuel costs due to improved plant efficiency.
- Significant reduction in CO₂ emissions.
- Excellent availability, comparable with that of existing subcritical plant.
- Excellent part load efficiency and flexibility.
- Plant costs comparable with subcritical technology and less than other clean coal technologies.
- Much reduced NO_x, SO_x and particulate emissions.
- Compatible with biomass co-firing.
- Can be fully integrated with appropriate CO₂ capture technology.

⁶ DTI Best Practice Brochure No. BPB005, "Refurbishment of Yaomeng Power Plant", DTI/Pub URN 03/1065, August 2003

EXCELLENT PART LOAD EFFICIENCIES

Efficiencies of supercritical power plant are less affected by part load operation. For example, available data suggest reductions in plant efficiency for supercritical units of ~2% at 75% load, compared with a 4% reduction in efficiency for subcritical plant under comparable conditions. This is because, when compared with subcritical conditions (180 bar), the heat input to the boiler to reach 540°C is 100kJ/kg lower for supercritical conditions. Although this results in lower heat capacity of the steam, in the steam turbine the higher kinetic energy level of the steam compensates for this effect. The absolute efficiency reduction at 75% load at the Hemweg 8 plant is 0.5 percentage point, considerably less than 2% of the 42% net LHV design cycle efficiency.³

COSTS COMPARABLE WITH SUBCRITICAL TECHNOLOGY

A new 'best practice' supercritical boiler/turbine power plant (including FGD and SCR) EPC specific price would be around

800 Euros/kWe gross (around £530/kWe Europe 2000 prices; Euros 1.5/£).⁷ This is no more expensive than a subcritical plant and less expensive than an IGCC for which EPC prices are quoted as US\$1250/kWe - US\$1440/kWe (approx. £700/kWe - £800/kWe; assuming US\$1.8/£) for new plant.⁸ Investment costs of existing IGCC plants have been between 1500 and 2000 Euros/kWe (£1000/kWe - £1333/kWe; Euros 1.5/£).⁹

Table 3 below summarises the levelised cost of electricity (CoE) for a nominal 600MWe gross bituminous coal-fired power plant. For the purposes of the comparison, the total investment cost (TIC) is taken as the EPC price plus owner's costs of 5% of the EPC price and contingency of 10% of the EPC price. Project life used for the economic appraisal was 25 years.

MUCH REDUCED NO_x, SO_x AND PARTICULATE EMISSIONS

By combining the advantages of higher efficiency plant (lower emissions per MWe)

Table 3. Levelised CoE for nominal 600MWe gross bituminous coal-fired power plant

Parameter	Units	Subcritical power plant	Supercritical power plant
Plant size	MWe gross	600	600
Plant net efficiency	% LHV	38.0	46.0
Total investment cost (TIC)	Euros/kWe gross	874	920
Fuel price	Euros/GJ	1.6	1.6
Load factor	%	85	85
Cost of electricity (CoE)	c/kWh	3.5	3.3
	UK p/kWh	2.3	2.2
Breakdown of CoE			
Fuel	c/kWh	1.5	1.2
Capital	c/kWh	1.3	1.4
O&M	c/kWh	0.7	0.7

⁷ Reference Power Plant North Rhine-Westphalia (RPP NRW) VGB PowerTech 5/2004

⁸ G Booras and N Holt, EPRI, "Pulverised Coal and IGCC Plant Cost and Performance Estimates" Gasification Technologies 2004, Washington DC, October 3-6, 2004

⁹ Francisca Garcia Pena, "Advanced Gasification Systems", presented at PowerClean / EPPSA Seminar, Brussels, 12 April 2005

and best available air pollution control technologies, the best practice plant offers significantly reduced emissions.

CARBON DIOXIDE CAPTURE

The best practice supercritical boiler/turbine plant can be fitted with carbon dioxide capture equipment either when first built or as a retrofit. Two technologies - both proven at smaller scale - are being developed. These are:

- amine scrubbing (post-combustion capture)
- oxyfuel firing (pre-combustion capture).

More details are given in Section 7 below, under Carbon Dioxide Capture and Storage.

7. CURRENT DEVELOPMENTS OF BEST PRACTICE FOR SUPERCRITICAL TECHNOLOGY

ASC technology is continuing to develop with collaborative R&D programmes underway in Europe, the USA and Japan.

MATERIALS DEVELOPMENT FOR STEAM TEMPERATURES 600°C - 650°C

Studies are underway which will progressively increase the temperatures and pressures that can be employed using ferritic and austenitic steel tubes, headers and piping. The studies encompass base materials, weldments and dissimilar metal transition welds.

The Boiler Materials Sub-Group (within the EU AD700 project) has seen the development and validation of the European steel E911 and its approval as ASME Code Case 2327, the confirmation of as-welded properties of T23 material, the development and testing of a number of weld consumables for the 9-12% Cr martensitic steels, and the development of a new austenitic steel based on Esshete 1250. The Steam Turbine Group concentrated on the optimisation of the 9-12% Cr steels for rotor forgings and valve chests, and a programme of mechanical and creep testing has been going on continuously during the tenure of the

European Co-operation in the field of Scientific and Technical Research (COST) programmes. This has allowed both the fabrication of full-sized rotor forgings and valve chest castings so that properties can be compared to those from semi-commercial melts, and the continuation of creep testing from one COST programme to the next, so that in some cases, test times of more than 100,000 hours have been achieved.

The new programme, COST 536, takes as its targets the extension of the temperature limits to martensitic materials with a 100,000 hour creep strength of 100MPa at 650°C. It also covers an increasing understanding of microstructural evolution in advanced materials and weldments, steam oxidation mechanisms and coating degradation mechanisms. The latter two are particularly necessary for the 9-12% Cr steels at metal temperatures of around 650°C, where steam oxidation rates rather than creep strength become life limiting.

A further collaborative initiative aimed at materials for supercritical plants is being pursued with organisations in the USA, again with support on the British side from the UK DTI.

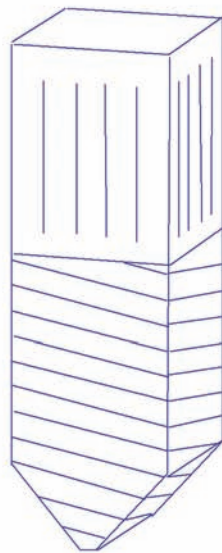
INNOVATIVE POSIFLOW™ LOW MASS FLUX SUPERCRITICAL BOILER

The latest refinement in Benson once-through boiler technology is the vertical tube low mass flux furnace, offered in place of the spiral wound furnace (see Figure 9). Development of this technology is well advanced, based on collaborative effort between Mitsui Babcock and Siemens.

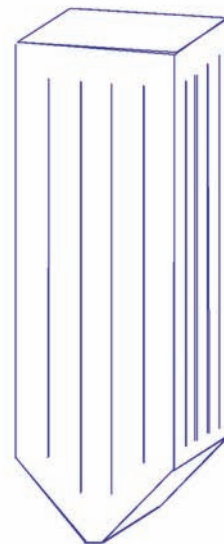
The spiral wound furnace uses a relatively high mass flux to provide adequate cooling of the furnace walls. In the low mass flux case, the inside surfaces of the tubes are 'rifled' (see Figure 10) to impart a rotational movement to the fluid as it flows up the tube. This forces the denser (more heat absorbing) fluid to the periphery of the fluid column (where it is in direct contact with the inner surface of the tube).

The furnace walls from the hopper inlet to the furnace arch nose level are of vertical tube

- High mass flux with negative flow characteristics
- High pressure drop
- High BENSON minimum load
- Additional support system



- Low mass flux with positive flow characteristics
- Low pressure drop
- Low BENSON minimum load



Spiral Wound Furnace vs Vertical Tube Furnace

Figure 9. Comparison of spiral wound and vertical tube furnace arrangements



Figure 10. Comparison of regular tube (left) and specially optimised ribbed tube (right)

membrane wall construction. The low mass flux technology inherently ensures a positive flow characteristic, which means the tubes with higher than average heat pick-up have a higher than average water flow without the need for adjustable orifices or similar means to control temperature. An optimised profile of the internal ribs of the low mass flux vertical furnace tubes is essential (see Figure 10). The main advantages identified are:

- Lower capital costs:
 - Self-supporting tubes, hence simplifying part of the boiler support system
 - Elimination of transition headers at spiral/vertical interface
 - Simpler ash hopper tubing geometry.
- Lower operating costs:
 - Lower overall boiler pressure drop, hence lower auxiliary power load resulting in higher plant output and higher efficiency
 - 'Positive flow characteristic' automatically compensates for variations in furnace absorptions compared to the negative flow characteristics of the spiral furnace
 - Simple and economic tube repair
 - Simple start-up system; a start-up circulation pump is not required
 - Reduced slagging of furnace walls
 - Lower part loads down to 20% are possible while maintaining high steam temperatures.

The significant benefits of this technology include:

- **Improved operational and load-following capability:** as the boiler can cope with varying heat absorption with significantly reduced risk of boiler tube overheating

- **Improved boiler availability:** as the risk of boiler tube failure from overheating and high stresses from local tube-to-tube metal temperature differentials are significantly reduced
- **Ability to increase the boiler furnace outlet steam temperature for a given boiler tube wall material:** as the tube-to-tube metal temperature differentials are significantly reduced
- **Significantly lower boiler pressure losses:** than for a typical high mass flux furnace tube design, resulting from the low water mass flux and hence reduced boiler feed pump power consumption
- **Easier slag removal:** resulting from the vertical tube orientation.

Several European manufacturers, all licensees of Siemens' Benson technology, are offering low mass flux vertical tube designs.

Mitsui Babcock is in the unique position of having an established and successful reference plant for Posiflow™ low mass flux technology through the retrofit project at Yaomeng Unit 1 Power Plant in China.⁶

Situated in Henan Province, PRC, Yaomeng Power Plant consists of four units of 300MWe coal-fired boilers. Unit 1 (shown in Figure 11) and Unit 2 entered service in the mid-1970s. They were high mass flux, once-through, subcritical universal pressure (UP) boilers, designed for base load operation to generate main steam at 570°C. A full height division wall connected in series with the outer walls was used to create a symmetrical twin furnace layout, with tangentially firing burners. The furnace width was 17m, the depth 8m and the water mass flux 1800kg/m²s. The design required that flow measuring devices and individual valves were needed to preset the flow distribution to each furnace wall circuit during the commissioning stages.

From 1992 onwards, after overheating in the pressure parts led to a restriction of 545°C on the main steam temperature, the maximum output was reduced to 270MWe. The boiler's intrinsic intolerance to load change and

operation below 230MWe was also problematic, and the prospect of more onerous emissions legislation was thought likely to impose further restrictions or even closure. Instead, Yaomeng Power Generation Limited (YPGL) chose plant upgrade.

Mitsui Babcock's main objectives in delivering the refurbishment to YPGL were to:

- permit the achievement of full design load
- give the boiler full operational flexibility in following load demand
- maintain stable operation over the full load range.

The scope of work for Mitsui Babcock centred on the upgrade of the furnace pressure parts and improvement of the burners, start-up system and control philosophies.

The new Posiflow™ furnace arrangement is shown in Figure 12; the three-dimensional, Computer Aided Drawing (3-D, CAD) model was generated as part of the new boiler design process. Careful selection of the new furnace wall components has enabled the



Figure 11. Yaomeng Unit No.1 before refurbishment

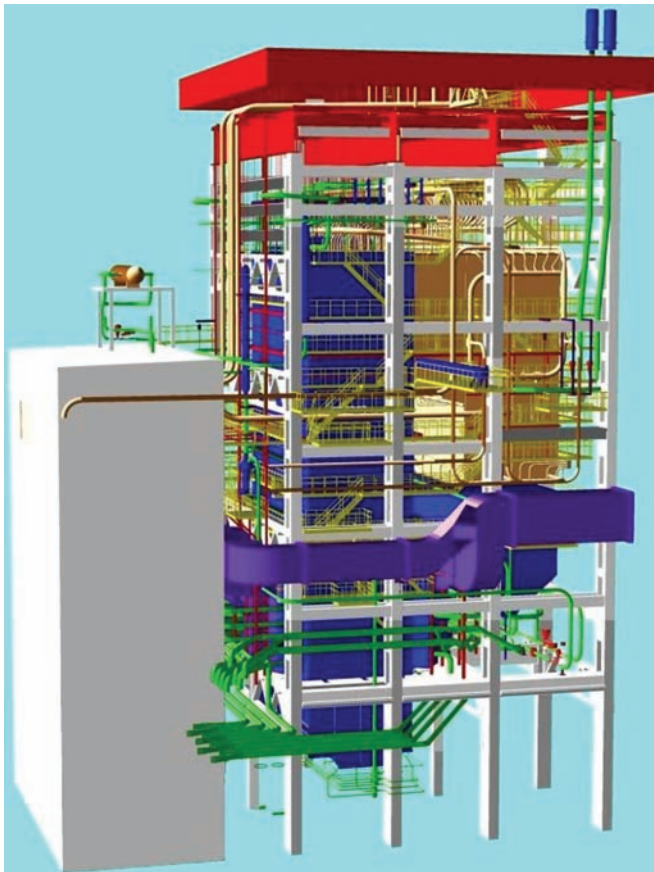


Figure 12. CAD model of the refurbished Yaomeng boiler

existing boiler footprint and main support structure to be retained, together with the simplification in the feedwater connections to give a parallel flow regime for the furnace, and division walls to reduce pressure losses even further.

The refurbished Yaomeng boiler performance objectives were all achieved:

- It was evident from the significant reduction in the exit temperature differentials between adjacent tubes that the vertical ribbed tubing was performing well. Thus the self-regulating flow characteristics achieved with Mitsui Babcock Posiflow™ boiler technology had been demonstrated, a world first in commercial power generation using utility boilers.
- Peak power output has been increased from 270MWe to 327MWe, and the boiler has

been formally uprated to 310MWe.

- Operation without fuel oil support was difficult at any part load condition before the upgrade; it is now possible down to 40% BMCR.
- The load-following capability has also been much improved and boiler thermal efficiency has increased from 90.3% to 91.4%.
- The new start-up system has decreased boiler start-up and shutdown times appreciably, with cold start-up times being reduced by up to 60 minutes.

AD700 ASC PF-FIRED POWER PLANT (350 bar / 700°C / 720°C)

In seeking to maximise the efficiency of coal-fired power plant and at the same time minimise the environmental effects, European industry, including both manufacturers and power generators, launched the AD700 programme¹⁰ with the aim to raise the net efficiency of pulverised fuel power plant to over 50% when operating with a steam temperature in the 700°C region and pressure in the range of 350-375 bar. The project is supported by the European Commission and is being executed in six phases, see Figure 13.¹⁰

In **Phase 1** (1998-2004), the following activities were carried out:

- materials have been identified
- thermodynamic cycles have been agreed upon
- feasibility studies showed competitiveness
- new boiler concepts with reduced amount of super-alloys have been assessed.

During **Phase 2** (2002-2005, with expected prolongation until 2007), supported by the European Commission in the frame of 6th Framework Programme, the following activities are underway:

- design and testing of critical components
- further studies on innovative design
- design of a CTF (Components Test Facility)
- assessment of a demonstration plant.

¹⁰ J Bugge, S Kjær, R Vanstone, F Klauke, C Stolzemberger, F Bregani, S Concari, "Review of the AD700 technology: a European route to clean combustion of coal", CCT 2005 Second International Conference on Clean Coal Technologies for our Future, Castiadas (Cagliari), Sardinia, Italy, 10-12 May 2005

Phase	Description	FP5					FP6					FP7							
		98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
1A	Conceptual feasibility																		
1B	Material property																		
2A	Basic design for Phase 3																		
2B	Materials property demonstration																		
3	COMTES700 (CTF, ETR)																		
4	Full Scale Demo Plant (FSDP)																		
5	Operation of FSDP																		
6	Feedback to partners																		

Figure 13. Development schedule for AD700 technology

The COMTES700 project, recently started, is supported by both the European Commission in the frame of the ECSC Programme and utilities belonging to the Emax Group, and deals with the realisation and testing of the CTF at the E.ON Scholven F power station in Germany.

In parallel, Mitsui Babcock and E.ON UK are investigating material properties and ultrasonic inspection methods for the higher temperature materials for 700°C plant, supported by the UK DTI.

The project has demonstrated that AD700 technology offers a feasible route to efficiency improvement and emission reduction. The economies of AD700 plant depend on the use of nickel-based alloys (including material grades 617, 740, 625 and possibly 263) and benefit from employing novel compact plant designs to reduce the length of the steam lines.

A number of other proposals to reduce the cost of expensive steam piping have been investigated and a concept from Mitsui Babcock has now been patented. It is a proposal for a double shell steam line named 'Compound Piping' with thermal insulation between the two shells, so the outer shell can be made from a cheaper material such as steel as it is protected from the high

temperatures by means of the insulation. The inner shell (the steam pipe) can be made from thin high-strength materials such as nickel-based alloys as it does not have to withstand the pressure.

CARBON DIOXIDE CAPTURE AND STORAGE

Recent studies have indicated the feasibility of carbon dioxide capture and the possibility of permanent storage underground in saline aquifers or depleted oil or gas reservoirs. The injection of CO₂ can also be used in enhanced oil recovery (EOR) and there are a number of projects worldwide that have demonstrated these concepts.

Mitsui Babcock and Alstom Power are participating in a number of studies (some completed, several underway, and supported by the IEA, the EU and the DTI) to explore the application of carbon capture to ASC boiler/turbine plant for both retrofit and new build. These studies address the technical and economic feasibility of retrofitting CO₂ capture using either of the two current candidate technologies, amine scrubbing or oxyfuel firing. Careful attention is being given to integration aspects in order to minimise the efficiency penalty of carbon capture so that ASC plant can be designed to be 'capture-ready'.

Figure 14 below summarises the amine scrubbing process concept. Absorption-based amine scrubbing processes are the only technologies currently available at the scale required for CO₂ capture from power plant. They are well suited to this, with some process modifications needed to overcome particular problems posed by some of the low concentration chemical species present in flue gas from power plant, particularly those with coal-fired boilers.

Most of the suggested modifications required have yet to be demonstrated at large commercial scale even though there are many paper studies which demonstrate their feasibility. This is because, as yet, there are no large-scale carbon dioxide capture plant operating on commercial power plant, although scale-up issues for plant of the expected size have been addressed in the oil and gas industry.

Impurities in the flue gas need careful consideration in the design of the amine scrubbing plant. In addition to this the recovery of carbon dioxide from the rich amine

stream from the absorber is highly energy-intensive. Care again is required in the design and plant integration activities to minimise significant export power loss.

Figure 15 opposite presents an indicative diagram for an oxyfuel CO₂ capture system. Note that, as shown, the oxyfuel flue gas recycle (FGR) is taken from downstream of the flue gas desulphurisation (FGD) plant, which assumes a high sulphur coal. For low sulphur coals, the FGD plant can be removed and the FGR stream may be taken from further upstream. For oxyfuel firing, an air separation unit is used to ensure that only oxygen is admitted to the furnace for combustion.

This has the advantage of significantly reducing the flue gas volumes, but the separation process has a performance penalty.

Mitsui Babcock and Alstom Power, together with Fluor, Air Products and Imperial College, provide further information on the application and process integration of the above CO₂ capture technologies for new-build ASC PF-fired CO₂ capture power plant.^{11,12}

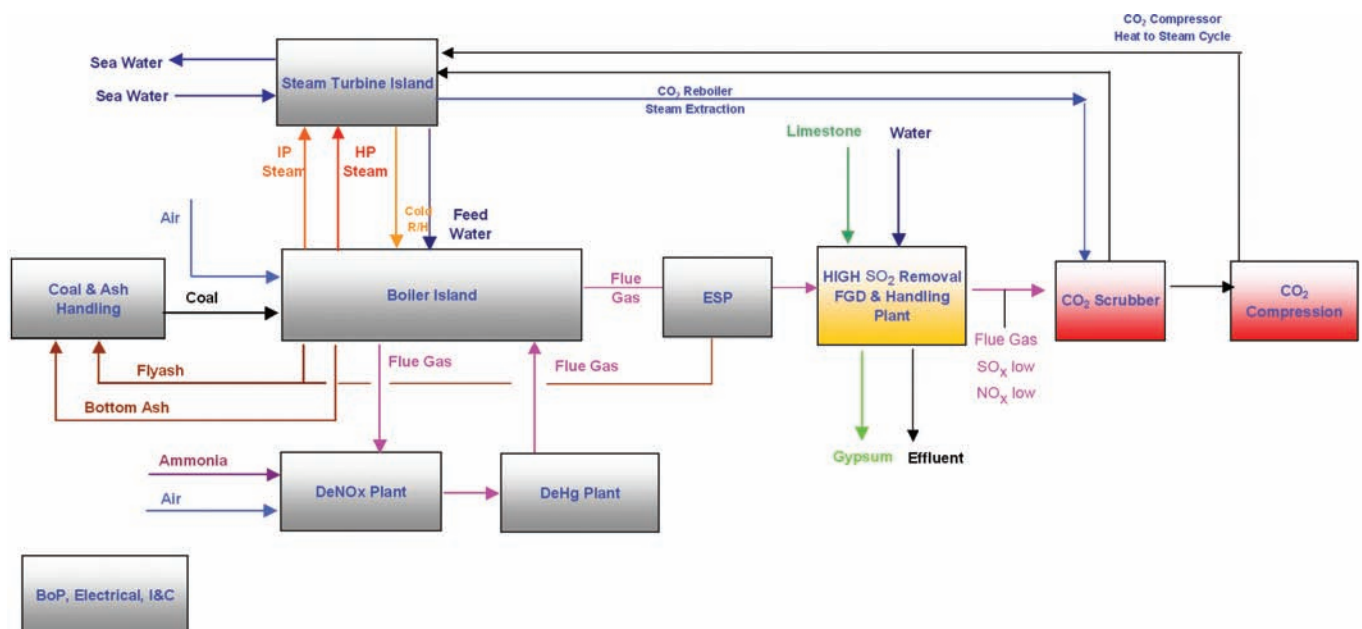


Figure 14. Amine scrubbing process for CO₂ capture

¹¹ C A Roberts, J Gibbins, R Panesar and G Kelsall, "Potential for Improvement in Power Generation with Post-Combustion Capture of CO₂", Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. Peer-reviewed Papers, Vancouver, BC, September 5-9, 2004

¹² D J Dillon, R S Panesar, R A Wall, R J Allam, V White, J Gibbins & M R Haines, "Oxy-combustion Processes for CO₂ Capture from Advanced Supercritical PF and NGCC Power Plant", Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. Peer-reviewed Papers, Vancouver, BC, September 5-9, 2004

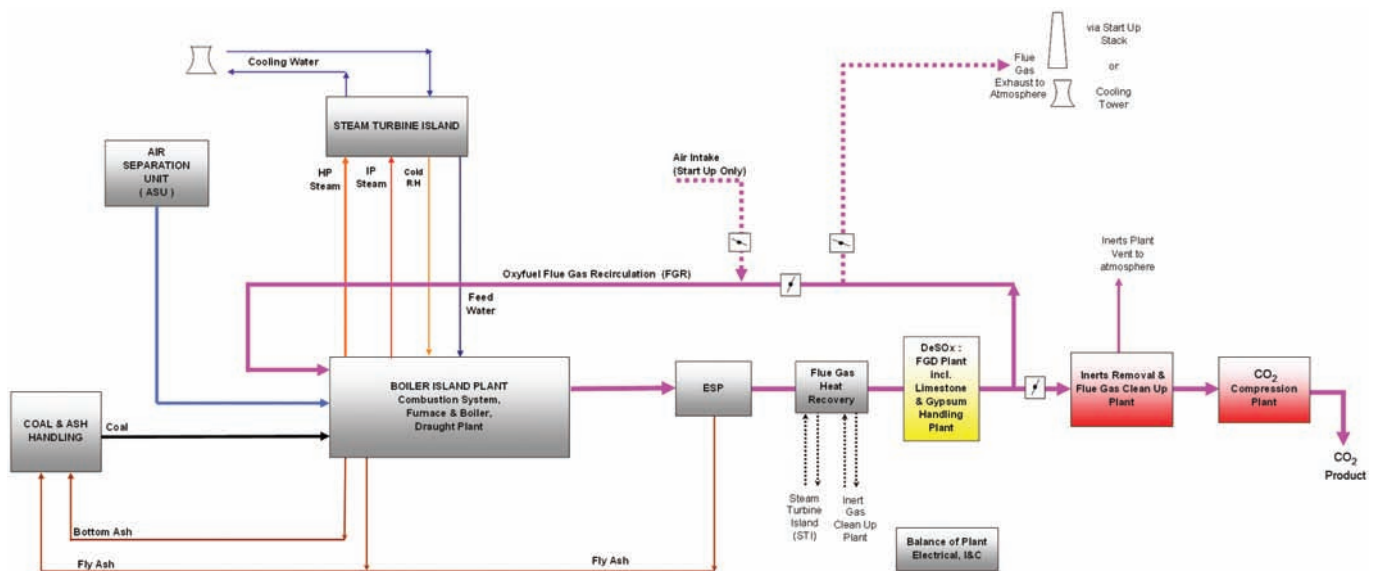


Figure 15. Indicative oxyfuel capture process (as shown for high sulphur coal hence FGD included)

Both of these CO₂ capture processes, amine scrubbing and oxyfuel combustion, are at the conceptual design stage and commercial demonstration plants are now being sought.

8. CONCLUSIONS

1. Commensurate with the twin-track approach identified:

- Track 1 : retrofit and new build increasing plant efficiency, biomass co-firing, etc.
- Track 2 : retrofit and new build integration of CO₂ capture plant to facilitate carbon capture and storage (CCS).

Technology developments by Mitsui Babcock and Alstom Power make them well placed to deliver ASC coal-fired power plant using high efficiency best practice boiler/turbine technologies.

2. The ASC coal-fired boiler/turbine technologies described will deliver significant reductions in CO₂ emissions as net plant efficiency is increased; more than 20% reductions in CO₂ emissions, down to 700g/kWh corresponding to approximately 46% net LHV basis, is achievable from ASC technology compared with typical existing subcritical plant.

3. State-of-the-art best practice ASC PF-fired boiler and steam turbine plant is available from Mitsui Babcock and Alstom Power for a wide variety of coal types. Recent examples include Meri Pori, Hemweg, Avedoreværket, Nordjylland, Skærbæk, Staudinger, Duke Power, Changshu and Wangqu. These plants demonstrate that high levels of clean coal combustion, high overall cycle efficiencies and excellent plant availabilities can be achieved with state-of-the-art ASC PF-fired boiler and turbine technologies.

4. Mitsui Babcock's innovative Posiflow™ low mass flux, vertical tube, once-through boiler technology has been successfully demonstrated at Yaomeng.

5. The experience from the above allows us to define ASC BAT as 300 bar / 600°C / 620°C. Proven materials for ASC power plant (boiler, turbine and pipework) are now available to meet these steam conditions for a wide range of coal types.

6. Mitsui Babcock and Alstom Power remain committed to further developing their ASC boiler and turbine technologies to deliver fully integrated and optimised ASC PF-fired CO₂ capture power plant, covering realistic scenarios of capture and capture-ready for both retrofit and new ASC PF-fired power plant solutions.

9. UK COMPANIES: BEST PRACTICE TECHNOLOGY CONTACTS

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APPENDIX: Comparison of Power Plant Thermal Efficiencies

Comparison of published efficiency values for different types of power plant is difficult for several reasons:

- Differences in how the heating value of the fuel is calculated
- Differences in site conditions and especially condenser pressure
- Differences in plant design, such as single or double stage reheat when otherwise the plants are of similar design
- Whether gross or net efficiencies (and plant output) are considered, and what add-on equipment such as desulphurisation units are used.

The condenser pressure is commonly the most important factor, and going from a condenser pressure of 0.05 bar, which requires a cooling water temperature of 27-28°C, to 0.02 bar, with a cooling water temperature of 14-15°C, produces an extra three percentage points. Thus, for proper comparisons, all actual plant efficiencies ought to be recalculated to 'standard conditions' in order to be meaningful.

In Europe, efficiencies are expressed on the basis of lower heating value (LHV), which is the difference between the higher heating value (HHV which is the total amount of energy contained in the fuel) and the latent heat of evaporation of the water contained in the products of combustion. In some countries, such as the UK and Japan, power plant generating efficiencies are commonly defined merely in terms of higher heating value. However, the LHV is a more accurate assessment of the 'useful' energy of the fuel for plant where this water goes to the atmosphere in the flue gas stream. The ratio of HHV to LHV for a typical steam

coal is approximately 1.05:1.00. It will otherwise vary depending on coal composition and heat content. For fuels such as natural gas and biomass, with a higher hydrogen content, this ratio will be much higher. This complicates comparisons between different technologies and fuels.

When generating efficiencies are quoted as based on HHV, the electricity output is divided by the HHV of the fuel used. When they are quoted on an LHV basis, the output is instead divided by the LHV value of the fuel. Consequently, HHV generating efficiencies are lower than LHV generating efficiencies. For example, a coal-fired steam plant with an HHV efficiency of 40% has an LHV efficiency of approximately 42%, provided plant design and site conditions are the same.

A broad understanding of the current status of coal-based power plant can be gained from a comparison of several state-of-the-art steam plants around the world, as illustrated below:

Plant	Steam conditions MPa / °C / °C	Net thermal efficiency, %	
		HHV %	LHV %
Tachibanawan (Japan)	24.1 / 600 / 610	42.1	44
Tanners Creek (USA)	24.1 / 538 / 552 / 566	39.8	42
Nordjylland 3 (Denmark)	29.0 / 582 / 580 / 580	45	47.0
Niederaussem K (Germany)	27.5 / 580 / 600	42-43	45.2

The Japanese and US plants have relatively high condenser pressures compared to the Danish plant. The Niederaussem plant burns a lower grade lignite, whereas the others are fuelled with bituminous 'trading' coals.

Further information on the Carbon Abatement Technologies Programme, and copies of publications, can be obtained from:

Carbon Abatement Technologies Programme Helpline, Building 329,
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